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OPHIOLITIC PERIDOTITES FROM LIGURIA (NW ITALY): IMPLICATIONS ON RIFTING AND SUBDUCTION PROCESSES

Abstract. Studies on the petrology and geochemistry of mantle rocks contribute significantly to understanding the petrogenetic and kinematic processes governing the evolution of the lithosphere-asthenosphere system under different geodynamic settings. This paper summarizes present knowledge on mantle peridotites from the Ligurian sector (Voltri Massif and Northern Apennines) of the Alpine-Apennine chain. These upper mantle slices were emplaced during the Jurassic on the ocean-floor of the Ligure-Piemontese basin (LPB) through a pre-oceanic rifting stage under sub-continental conditions. Within the Ligurian sector of the Alpine-Apennine orogenic belt, mantle peridotites occur in various structural units (Beigua and Erro-Tobbio, Voltri Massif; Internal and External Ligurides, Northern Apennine), where they are frequently associated with MORB-type mafic intrusives and volcanics to form ophiolite sequences. Present knowledge highlights some basic features ruling the mantle history of the Ligurian ophiolitic peridotites. The External Liguride Units include large fragments of fertile lithospheric sub-continental mantle representing previous asthenosphere accreted to the lithosphere during Proterozoic times, and recrystallized to spinel-facies assemblages during thermal equilibration to the local geotherm (i.e., transformation into lithospheric mantle). The Erro-Tobbio fertile sub-continental peridotites from the Voltri Massif reveal a composite tectono-metamorphic history following an almost subsolidus non-adiabatic evolution during uplift. This decompressional path, related to the early pre-oceanic rifting in the Ligure-Piemontese basin, is consistent with mechanisms of tectonic unroofing following passive and asymmetric extension of the lithosphere. The Internal Liguride ophiolites include bodies of former asthenospheric residual mantle depleted by a Permian MORB-generating melting event. During uplift, they followed a subsolidus history and were intruded by gabbroic rocks. The mafic intrusives in turn record a sequence of deformation and subsolidus retrograde recrystallization, starting from high temperature (granulite/amphibolite) conditions. All these features are related to the pre-oceanic rifting stage. Fertile and depleted mantle peridotites and associated gabbros were later exposed on the sea-floor where they were overlain by continental and ophiolitic sedimentary breccias and MORB volcanics (i.e., the formation of a discontinuous and incomplete oceanic crust). Structural and petrological evidence prevent relating these ophiolite sequences to active mantle mechanisms as mature mid-ocean - transform fault settings. More properly, the Ligurian ophiolites are believed to represent the lithological associations which are expected to develop after continental breakup due to passive and asymmetric extension of the lithosphere. In fact, they consist of pre-Jurassic sub-continental rocks, unroofed and exposed on the sea-floor during the extensional processes, associated with late-Jurassic MORB-type basalts produced by partial melting of upwelling asthenosphere. The Permian age for the partial melting of some Internal Liguride residual peridotites gives indications on the age of rift inception: it is, in fact, almost coeval with the post-Variscan extension recorded by the Austroalpine and Southalpine units, recently interpreted as a signature of the late Paleozoic onset of extension within the Europe-Adria lithosphere. Some peridotite bodies from Liguria (i.e., those of the Voltri Massif) underwent a composite tectonic-metamorphic history during the Alpine evolution, which is mainly marked by antigorite- and antigorite + olivine + Ti-clinohumite-bearing associations. Other typical features of the peak metamorphic event are veins filled by the same olivine + Ti-clinohumite association. The developement of these assemblages appears to be roughly coeval with the widepread formation of eclogite facies Na-pyroxene + garnet associations in meta-gabbros, which are enclosed within the peridotite bodies as former MORB-type intrusive bodies and dykes. Typical subduction P-T paths have been estimated for the Voltri Massif units, with different eclogite climax conditions for the different units: 13 kb minimum pressure at 450-500° C has been inferred for the Beigua Unit, 25 kb and 600°C for the Erro-Tobbio Massif. Our investigations indicate that large volumes of peridotites participate in the subduction evolution, and that mantle ultramafics in high pressure environments develop in large modal proportion hydrated phases which are stable up to 25 kb. As a consequence, large amounts of water may be retained in the subducted slab. This fact has relevant consequences on rock rheology, subduction-related fluid circulation and magmatism.

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INTRODUCTION

Petrological, geochemical and isotope studies on mantle peridotites from both xenoliths and orogenic massifs provide significant contributions to our understanding of the petrogenetic and kinematic processes governing the evolution of the lithosphere-asthenosphere system under different geodynamic settings.

In recent decades, significant advances have been made on mantle petrology and geochemistry at the global scale. This allows a better understanding of both the large scale structure of the upper mantle, and the nature and spatial distribution of the major compositional heterogeneities. Several models of the mantle structure and composition have been discussed in recent times, according to the two-mantle model of Schilling (1973). Most of them agree on some basic assumptions:

1) there is almost undifferentiated lower mantle below 670 km and differentiated upper mantle above 670 km;

2) two main structural elements are present within the upper mantle: lithosphere and asthenosphere;

3) the lithospheric mantle varies in composition from sub-oceanic to sub-continental areas; the sub-continental lithospheric mantle, moreover, shows significant compositional differences depending on the composition and age of the overlying crust, i.e., depending on whether it consists of i) stable Archaean cratons, ii) Proterozoic or younger mobile belts.

Some of the discriminant features of the different mantle types are outlined in the following, according to the mantle model recently proposed by Menzies and Hawkesworth (1987). The lower mantle is believed to have undifferentiated compositions with OIB (Oceanic Island Basalt - type) isotopic signature. The asthenospheric mantle, which underlies both the oceanic and the continental lithosphere, shows a rather homogeneous and fertile chemical signature with dominant MORB (Mid Ocean Ridge Basalt - type) and localized OIB isotopic components. The sub-continental lithospheric mantle keel of stable cratons presumably differentiated and stabilized during Archaean times; it is characterized by compositions formerly strongly depleted in basaltic components, but subsequently enriched through time by introduction of melts and percolation of fluids. The Archaean keels thus show very heterogeneous isotopic compositions. The sub-continental lithospheric mantle of Proterozoic and younger mobile belts, orogenic belts and rift zones shows strong chemical heterogeneities ranging from rather fertile to severely depleted compositions. The isotopic signature varies from MORB- to OIB-types. The more fertile types are interpreted as former asthenospheric mantle material accreted by diapirism to the lithospheric mantle, whereas the more depleted types are believed to represent ancient oceanic mantle welded to the Archaean nuclei during collision of lithospheric plates.

Present-day sub-oceanic, lithospheric mantle shows rather homogeneous chemical composition, strongly depleted in basaltic components, and isotopic composition with a dominant MORB signature.

The aim of this paper is to update present knowledge on mantle peridotites from the Ligurian sector of the Alpine-Apennine chain. In recent decades, petrological, geochemical and structural studies have focused on the identification of slices of both lithospheric and asthenospheric mantle among the mantle peridotites of the Ligurian Alps and the Northern Apennines, which became emplaced on the Jurassic ocean floor of the Ligure-Piemontese Basin (LPB). Researches into the Ligurian ophiolitic peridotites help, moreover, to unravel the nature of the pre-oceanic extensional processes preceeding the opening of the Ligure-Piemontese basin, and leading to tectonic unroofing of the sub-continental, lithospheric mantle.

The investigations into the alpine metamorphic peridotites from the Ligurian Alps help to define the most significant trasformations related to subduction and high pressure metamorphism of mantle rocks.

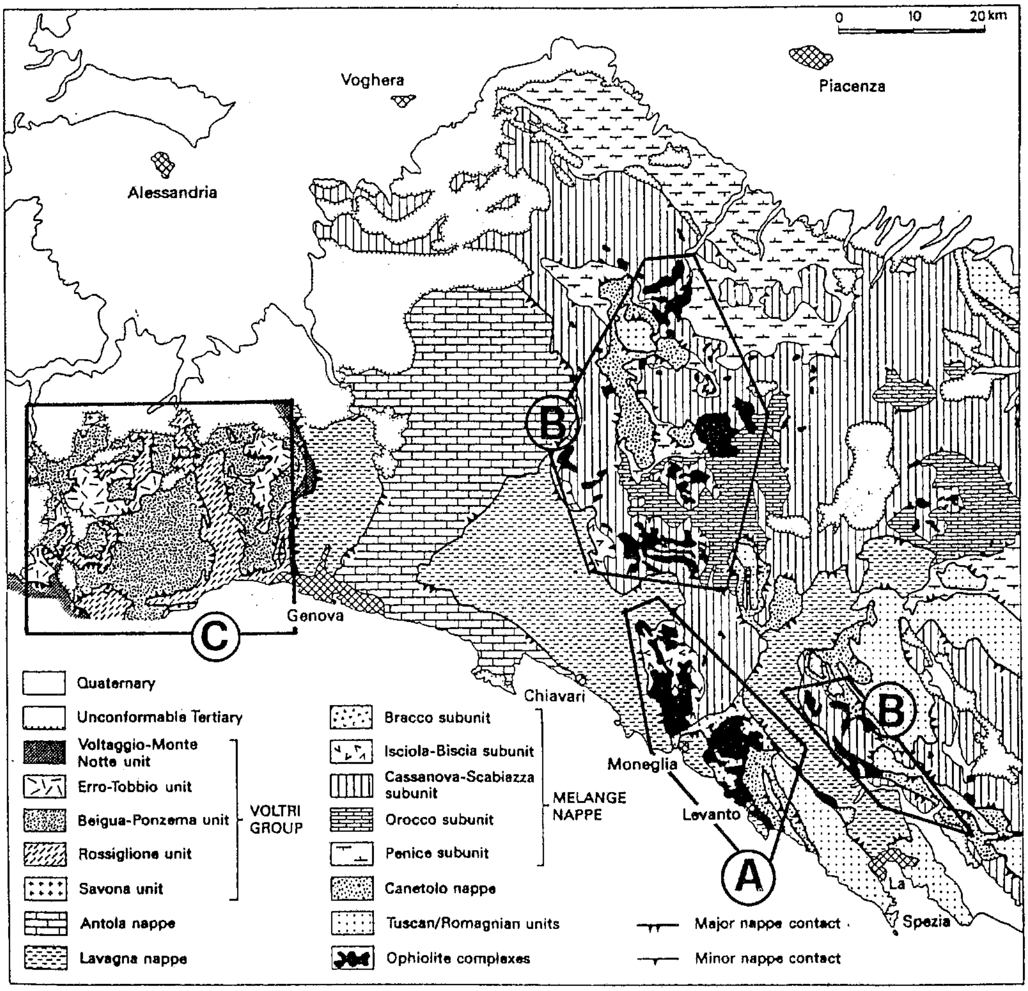

Fig. 1 — Tectonic sketch map of the Ligurian Alps and Northern Apennines. The ophiolite sequences of the Northern Apennines are reported in solid black. Squared areas: A = Internal Liguride Units; B = External Liguride Units; C = Voltri Massif.

GEOLOGICAL FRAMEWORK

In the Ligurian sector of the Alpine-Apennine chain, ophiolites and their sedimentary cover are mainly represented in the Voltri Massif (Ligurian Alps, Western Liguria) and in the Liguride Units (Northern Apennine, Eastern Liguria) (Fig. 1): ophiolitic peridotites are particularly abundant, either as basement of the basaltic and sedimentary cover or as huge isolated bodies. Ligurian ophiolites and peridotites are believed to represent remnants of the oceanic lithosphere of the Mesozoic Tethys, i.e., the Jurassic Ligure-Piemontese oceanic basin. The Voltri Massif ophiolites, moreover, have experienced intra-oceanic subduction since the Middle Cretaceous.

Within the Northern Apennines orogenic belt, mantle peridotites and related mafic rocks (ophiolites l.s.) occur in different units, supposedly depending on the different paleogeographic settings, which are traditionally referred to as the External and Internal Liguride Units, with respect to the Africa(E)-vergent tectonic transport. In the various units, ophiolites show different primary relationships to the associated sedimentary sequences (Decandia and Elter, 1969, 1972; Abbate et al., 1970a, 1970b; Braga et al., 1972; Pagani et al., 1972). In the Internal Liguride

(IL) units, ophiolitic mantle ultramafics and gabbroic intrusives represent the basement of the Jurassic MORB volcanics and the upper Jurassic-Paleocene sedimentary cover (radiolarian cherts, Calpionella limestones and Palombini shales). In the External Liguride (EL) units, peridotite and basalt bodies occur mainly as huge olistoliths within the Cretaceous-Eocene flysch sequences, where they are associated with continental detritus from both upper and lower crustal levels (Variscan acidic intrusives and volcanics, gneisses and micaschists, mafic granulites: Eberhardt et al., 1962; Pagani et al., 1972; Braga et al., 1975).

The tectonic source area for the EL lherzolites, basalts and continental crust detritus has been identified as the "Bracco Ridge" (Elter e Raggi, 1965), a submarine high which developed during the Cretaceous to separate the Ligurian realm into an Internal and an External basin. By contrast, petrographic and structural evidence suggests that EL peridotites and basalts were originally located close to a continental margin (like the Galicia Bank in the Eastern Atlantic ocean) or between the incoming newly formed passive continental margins (like Zabargad island in the Northern Red Sea) (Piccardo et al., 1990, with references therein). They were most probably emplaced on the sea-floor close to the newly formed Adria passive margin during the late Jurassic.

On the contrary, the IL ophiolites, which preserve primary stratigraphic contacts with the oceanic sedimentary sequences, were most probably formed in a more internal oceanic sector of the LPB.

The Voltri Massif of Western Liguria occupies the easternmost edge of the Ligurian Alps and is separated, to the east, from the Eastern Liguria Apennines by the Sestri-Voltaggio zone (Fig. 1). Towards the north, the Voltri Massif is unconformably covered by Tertiary sediments of the Piemonte basin. Previous work (Chiesa et al., 1975; Piccardo, 1977; Messiga e Piccardo, 1980) has shown that the large-scale structure of the Voltri Massif is dominated by a number of Europe (W)-vergent thrust sheets of alpine metamorphic ophiolites (Fig. 1), later dismembered by steep E-W and N-S trending faults. The polydeformed thrust sheets constituting the Voltri Massif include:

1) the Beigua-Ponzema (BE) Units, which consist of antigorite-serpentinites and eclogitized meta-gabbros (former gabbro-peridotite association): they are tectonically coupled with or stratigraphically covered by the Voltri-Rossiglione, Ortiglieto and Alpicella Units, which are mainly formed by sequences of meta-volcanics and calcschists (former MORB pillow basalts and their oceanic cover);

2) the overlying Erro-Tobbio (ET) Unit, which consists of metamorphic mantle peridotites and associated mafic dykes (Chiesa et al., 1975).

The Voltri Massif has tectonically overridden the Savona continental basement nappes, which consist mainly of gneisses, amphibolites and granitoids. These continental rocks show Alpine blueschist to greenschist facies metamorphism (Messiga, 1984).

Notwithstanding their Alpine evolution under HP subduction regimes, a bimodal distribution of the upper mantle rocks has been recognized within the Voltri Massif terrains (Piccardo, 1984). Depleted mantle protoliths characterize the ultramafic rocks of the BE unit, where they are associated with eclogitized gabbroic bodies and metamorphic volcano-sedimentary oceanic sequences, whereas rather fertile lherzolites occur within the ET unit (Ernst and Piccardo, 1979; Piccardo, 1984).

MANTLE ULTRAMAFICS

Two main groups of mantle ultramafics can be distinguished according to their compositional features (Piccardo, 1977; 1983; Beccaluva et al., 1984; Ottonello et al., 1984; Piccardo et al., 1990):

1) lherzolites, with abundant modal clinopyroxene (cpx) (10-15% by volume) and rather fertile bulk rock and mineral compositions (i.e., they are undepleted in basaltic components);

2) cpx-poor lherzolites (and harzburgites), with low modal cpx (less than 10% by volume)

and significantly depleted bulk rock and mineral compositions.

The different rock types crop out in separate structural units of both the Voltri Massif and the Northern Apennines. In fact, the more fertile lherzolites characterize the EL and ET units, whereas the more depleted peridotites are peculiar to the IL and BE units (Piccardo et al., 1990, and references therein).

UPPER MANTLE PRIMARY AND EVOLUTIONARY FEATURES

The External Liguride peridotite of the Northern Apennines

Notwithstanding their low grade alteration during the oceanic and orogenic evolution, the EL lherzolites of the Northern Apennines still retain paragenetic, structural-textural and compositional features related to their mantle history, which predates the sea-floor emplacement during the Jurassic opening of the LPB (Piccardo, 1983; Beccaluva at al., 1984; Piccardo et al., 1990). The EL lherzolites are commonly characterized by spinel (sp)-bearing paragenesis with equilibrium granular textures. Kaersutite - Ti-rich pargasite amphiboles are rarely found but show textural equilibrium with the sp-facies assemblage.

Sp-lherzolites have rather fertile bulk compositions (Piccardo, 1983; Beccaluva et al., 1984; Ottonello et al., 1984; Rampone et al., 1995a). Accordingly, they show relatively high Rare Earth Element (REE) concentrations: C1 (chondrite) normalized REE patterns are almost flat at 1-2 times C1, with a slightly negative LREE fractionation. Their constituent minerals, according to the bulk composition, have relatively high concentrations of fusible (i.e., basaltic) components. Clinopyroxene, in particular, shows rather flat C1 normalized REE patterns, with absolute REE values higher than 10 times C1 (Rampone et al., 1993; Piccardo et al., 1994; Rampone et al., 1995a) (Fig. 2).

From Sr and Nd isotope investigations, EL lherzolites record depleted isotopic signatures, typical of MORB-type mantle (Rampone, 1992; Rampone et al., 1995a). Consistent model ages for both Sr and Nd systematics reveal that the partial melting event responsible for present isotopic depletion may have occurred during the Proterozoic (Rampone, 1992; Rampone et al., 1995a).

The EL sp-lherzolites frequently show pyroxenite bands which, according to bulk and mineral compositions, have been interpreted as the result of magmatic events (partial melting, melt segregation and crystallization), probably developing under high T and P conditions within the upper mantle (Piccardo et al., 1990; Rampone, 1992). A similar interpretation has been proposed for analogous mafic layers in alpine peridotites and pyroxenite xenoliths in alkaline basalts (Menzies and Hawkesworth, 1987) from worldwide occurrences.

A subsequent stage of recrystallization at lower T (and probably P) conditions is suggested by thermobarometric estimates on the sp-bearing association (Beccaluva et al., 1984; Rampone, 1992), and by the presence of Ti-pargasite amphiboles, whose upper thermal stability in ultramafic systems and under mantle conditions has been experimentally determined (Jenkins, 1983; Oba, 1980). This indicates that a complete annealing sp-facies recrystallization occurred at temperature conditions below 1000-1100°C.

The above petrological, geochemical and structural evidence indicates the following sequence (Piccardo et al., 1990, 1994, and references therein):

1) an early composite upper mantle history under high temperature and pressure conditions. This evolution most probably developed under super-solidus (partial melting) conditions and was responsible for the chemical and isotopic features of the EL lherzolites;

2) a significant cooling under decompression, and a subsequent complete annealing recrystallization to sp-bearing assemblages, in the presence of fluids.

As a consequence, the EL lherzolites equilibrated at lithospheric mantle depths under P-T conditions consistent with an intermediate geothermal gradient for a non-cratonic continental lithosphere. Accordingly, the annealing sp-facies recrystallization represents the final stage in

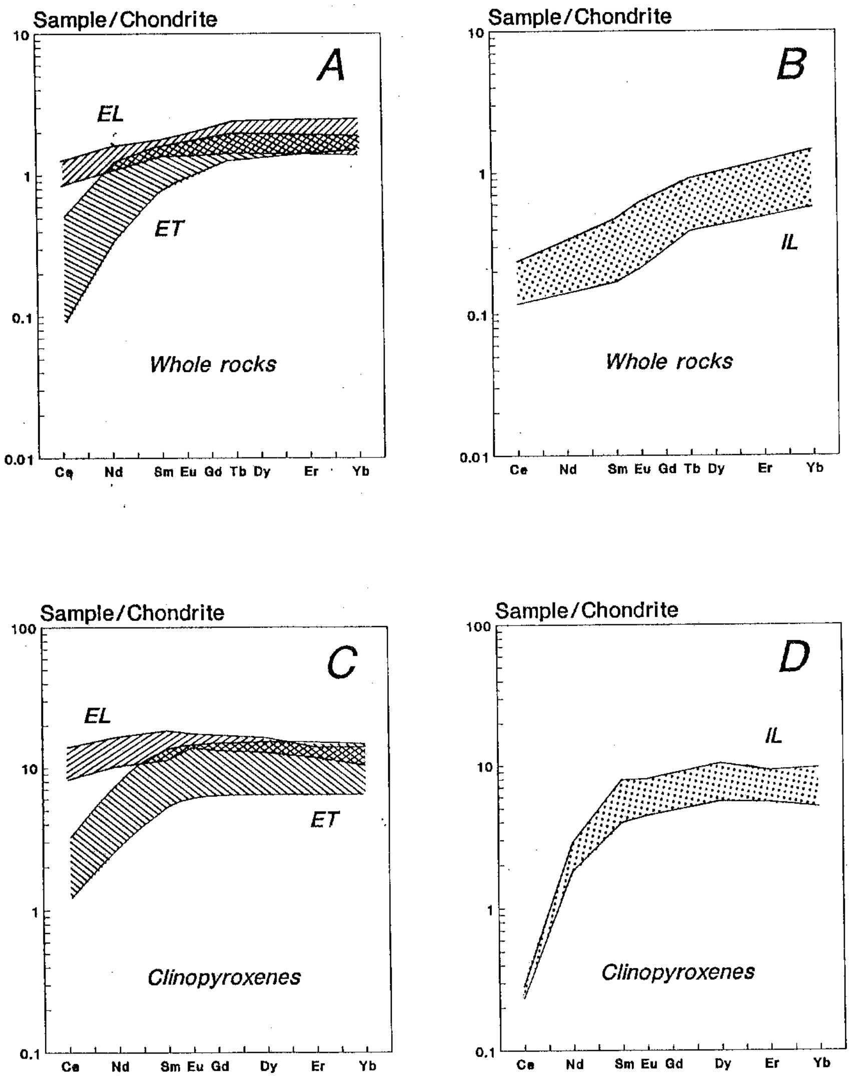

Fig. 2 — Representative chondrite (C1) normalized REE patterns in whole rocks (A, B) and clinopyroxenes (C, D) from the Erro-Tobbio (ET), External Liguride (EL) and Internal Liguride (IL) peridotites (data from: Ottonello et al., 1979; 1984; Rampone, 1992; Rampone et al., 1995a and b).

thermal and textural-paragenetic equilibration within the lithosphere of mantle material accreted from asthenospheric levels.

A subsequent composite evolution of the EL lherzolites is marked by widespread partial recrystallization to plagioclase (pl) - bearing assemblages in the granular rocks (Piccardo, 1977; 1983; Beccaluva et al., 1984), and by the development of tectonite fabrics accompanied by progressive dynamic recrystallization to sp- and pl-peridotite associations.

Structural, compositional and thermobarometric data indicate a subsolidus evolution under decompression and decreasing temperature (Piccardo et al., 1990, 1995; Rampone, 1992).

Sm-Nd dating of cpx-pl pairs from the pl-bearing assemblage gives an early Jurassic minimum age for recrystallization of the sp-lherzolites under pl-stability conditions (Rampone, 1992). This age is consistent with the inferred timing of the late rifting stage in the LPB.

In conclusion, the EL lherzolites are interpreted as sub-continental lithospheric mantle

(Piccardo et al., 1990, and references therein), generated by early processes of asthenospheric accretion to the lithosphere which operated in the Proterozoic (Piccardo et al., 1995; Rampone et al., 1995a). During the pre-Jurassic rifting and the Jurassic opening of the LPB, the EL sub-continental lithospheric mantle was progressively exhumed towards shallow levels, tectonically unroofed and exposed on the newly formed ocean-floor.

The Internal Liguride peridotite of the Northern Apennines

The IL cpx-poor peridotites of the Northern Apennines are frequently strongly serpentinized, but in some outcrops (i.e., at Mt. Fucisa) they are still relatively fresh and preserve granular textures and sp-bearing assemblages related to the mantle history. Bulk and clinopyroxene compositions are rather homogeneous and significantly depleted (Beccaluva et al., 1984; Ottonello et al., 1984; Rampone, 1992). The bulk rock C1 normalized REE patterns show a strong progressive fractionation from HREE to LREE at concentration levels never exceeding 1 time chondrite. Clinopyroxenes show very low Ti, Na contents and C1 normalized REE patterns steeply plunging at LREE, and almost flat from M- to HREE at 7-10 times C1 (Fig. 2).

On the basis of the depleted chemistry, the IL peridotites have been interpreted as refractory residua after MORB-generating low pressure partial melting (Piccardo, 1983; Beccaluva et al., 1980, 1984; Ottonello et al., 1984).

Thermobarometric estimates for the sp-bearing association (Beccaluva et al., 1984) indicate high temperature (1150-1200°C) equilibration. The sp-bearing assemblage is considered a near-solidus recrystallization after melt extraction.

Isotope data on separate cpx indicate (Rampone, 1992) that the IL peridotites are characterized by very high Nd and Sr isotopic ratios: this signature is compatible with residual mantle after MORB generation. A Permian age may most probably be envisaged for the MORB-generating partial melting (Rampone, 1992; Rampone et al., 1995b), i.e., an age significantly older than the exposure age of peridotites on the ocean-floor and spatial association with the late Jurassic MORB-type basalts (Piccardo et al., 1995).

Late evolution stages are marked by the appearance of subsolidus recrystallization of plagioclase- bearing assemblages and by widespread plagioclase enrichment in peridotites. The former features are indicative of cooling during shallow emplacement (Beccaluva et al., 1984), whereas the latter could be related to in situ crystallization of small volumes of exotic trapped melt (Rampone, 1992).

The IL peridotites are intruded by huge bodies and dykes of gabbroic rocks. Both peridotites and gabbros show localized plastic deformation and a composite recrystallization history postdating the gabbro intrusion. In the gabbro masses and dykes the metamorphic cycle generally starts from granulite/amphibolite facies and gradually retrogrades to lower (e.g., greenschist) conditions (Cortesogno and Lucchetti, 1984): this metamorphic evolution preceeded their ocean-floor exposure, low grade oceanic alteration, deposition of ophiolitic breccias and late extrusion of MORB pillowed basalts (i.e., the formation of a discontinuous oceanic basaltic crust).

In conclusion, the IL ophiolites have so far been classically interpreted as ophiolitic sequences better approaching an idealized oceanic lithosphere, either created within an embrionic ocean by symmetric passive extensional mechanisms (Decandia and Elter, 1969; Piccardo, 1977, 1983) or developing along slow spreading ridges (Barret and Spooner, 1977) or at transform-ridge intersections (Abbate et al., 1984).

Most of these models have recently been questioned by new petrological and isotope investigations (Rampone, 1992, Piccardo et al., 1995; Rampone et al., 1995b): these data highlight a more composite history of mantle rocks and related mafic intrusives. Large age differences have been revealed, moreover, between rocks (asthenospheric residual mantle and MORB pillowed basalts) which might have been born during the same event of mantle partial melting and melt intrusion and extrusion, as is supposed for a normal mid-ocean ridge-born oceanic lithosphere.

Mantle peridotites, in particular, underwent MORB-generating partial melting under sp-facies conditions during the Permian; they were subsequently exhumed towards shallower structural levels following subsolidus paths, and, later on, emplaced on the Jurassic ocean-floor. During uplift they were intruded at various depths (≥ 12 km) by gabbroic bodies and dykes, suffering further subsolidus evolution from granulite/amphibolite to lower grade conditions, prior to being exposed on the ocean-floor and capped by MORB basaltic volcanites.

The Beigua serpentinite of the Voltri Massif

The mantle protoliths of the Beigua antigorite serpentinites pervasively recrystallized on ocean floor and during the Alpine orogeny. These transformations occurred in the presence of water and almost completely overprinted the precursor mantle fabrics and assemblages.

Only in a few sectors of the Beigua unit have such features been preserved, due to the low strain and slow kinetics of the Alpine transformations. In this case, relic mantle tectonite fabrics are highlighted by the spatial distribution of a few relic porphyroclasts of mantle Cr-rich spinel, Cr-rich clinopyroxene with relatively low Na and Al contents, and minor olivine.

Clinopyroxene compositions, together with the high Cr content of spinel, have been interpreted as the residual signature of a significant degree of depletion suffered by the mantle protoliths.

On the basis of these features, it has been inferred that precursor mantle rocks were depleted peridotites similar to those from the Internal Liguride units of the Northern Apennines (Piccardo, 1984).

The Erro-Tobbio peridotite of the Voltri Massif

The ET peridotite body of the Voltri Massif, although involved in the Alpine collision of the Europe and Adria plates, preserves km-scale coherent volumes of unaltered lherzolite which almost completely retain mantle textures and assemblages. Besides early petrological investigations (Ernst e Piccardo, 1979; Ottonello et al., 1979), recent studies have unraveled a composite (tectonic and metamorphic) upper mantle evolution, which predates their shallow emplacement during the rifting stage of LPB (Piccardo et al., 1990,1992; Hoogerduijn Strating et al., 1990,1993; Vissers et al., 1991).

The ET mantle peridotites mainly consist of partly serpentinized fertile lherzolites which commonly show sp-bearing paragenesis with equilibrium granular textures. They locally preserve rounded orthopyroxene (opx) + sp clusters indicative of garnet-bearing associations prior to the sp-facies recrystallization (Hoogerduijn Strating et al., 1990,1993).

Available chemical data on ET peridotites (Ernst and Piccardo, 1979; Ottonello et al.,1979; and unpublished data) show a large compositional range and an overall slightly depleted signature. Bulk-rock C1-normalized REE patterns are almost flat (at less than 2 x C1) from H- to MREE, and differently fractionated from M- to LREE (Fig. 2).

Sp-lherzolites commonly show pyroxenite bands with strongly depleted peridotite walls, as a result of deep seated magmatic events. The pyroxenite layers locally exhibit isoclinal folds showing hinge structures completely recovered by granular sp-bearing equilibrium textures (Hoogerduijn Strating et al., 1990;1993; Vissers et al., 1991). This evidence points out that the lherzolites were plastically deformed after pyroxenite formation, and prior to the static, sp-facies equilibrium recrystallization.

Thermobarometric estimates ($T < 1100\,°C$ and P about 20 kb; Ernst and Piccardo, 1979; Hoogerduijn Strating et al., 1993) indicate that the spinel-facies recrystallization occurred under relatively high-pressure conditions, but at temperatures significantly lower than the dry solidus for fertile upper mantle compositions. Such P-T estimates are consistent with an intermediate (neither cratonic nor mid-oceanic) lithospheric thermal gradient.

Rare Ti-rich pargasitic amphibole is preserved in equilibrium with the sp-bearing assemblage, as described for the EL lherzolites. Its presence further constrains the temperature (not exceeding 1100°C) estimate for the sp-facies recrystallization.

The above observations suggest that:

1) the pyroxenite formation represents an early magmatic stage, possibly developed under high pressure conditions, close to the dry solidus;

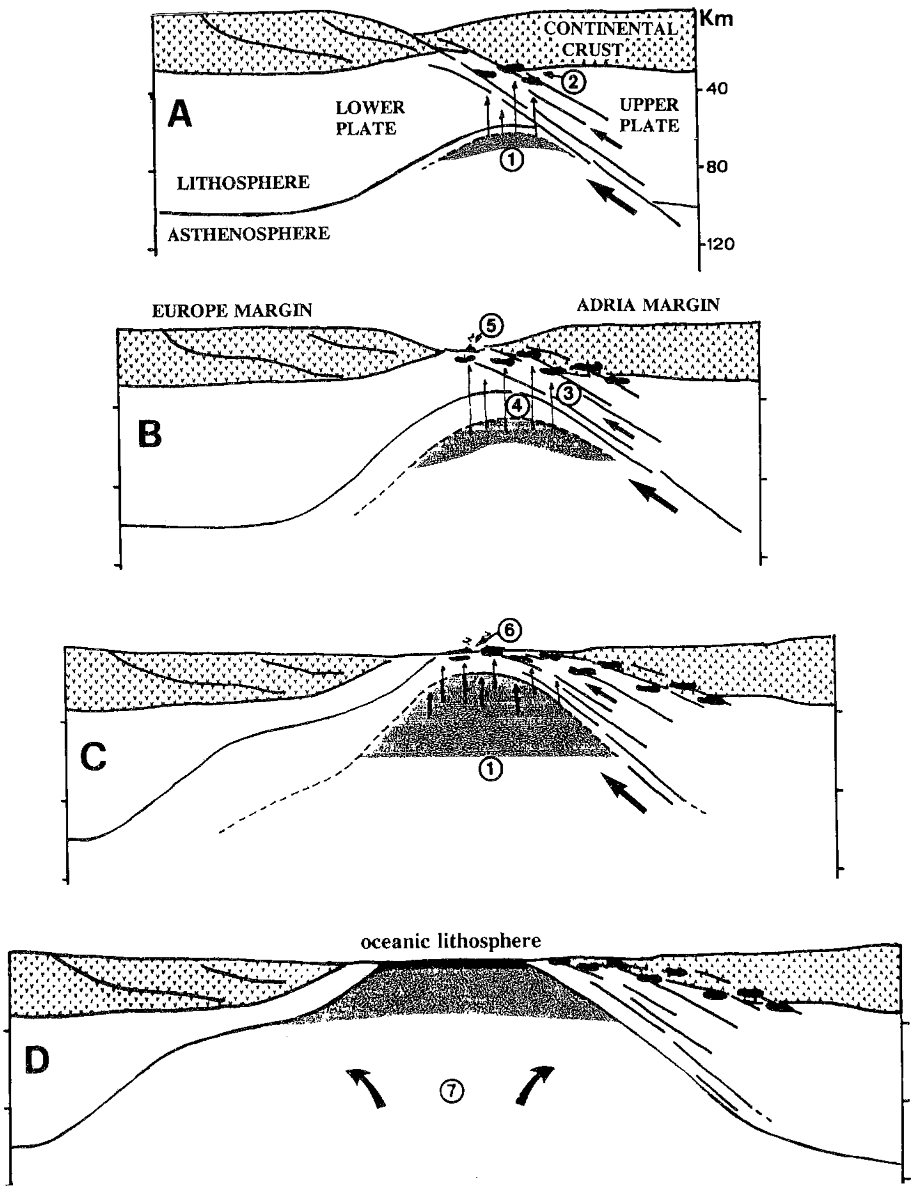

Fig. 3 — Geodynamic evolution from Permian rift to Jurassic continental breakup and ocean formation in the Ligure - Piemontese Basin along an east-west section. Besides the extensional processes, only Permian basaltic magmatism and intrusion of mantle derived melts (in black) into the extending Adria lithosphere are here considered. Late Variscan crustal magmatism is not considered; superficial rift structures have been omitted. Passive and asymmetric rift of the continental lithosphere, starting most probably from the Permian. **A.** The passively upwelling asthenosphere undergoes early stages of partial melting (1), leaving Permian residual mantle (4) and producing the primary melts for the Permian mafic-ultramafic intrusions (2) along the crust-mantle boundary and possibly also within the continental crust. **B.** More evolved rifting stage (Jurassic) leading to breakup of the continental crust and exposure of sub- continental lithospheric mantle (3). The upwelling asthenosphere undergoes more diffuse partial melting. This stage could correspond to the primary association of lithospheric mantle and MORB intrusives, sporadically cut by MORB basaltic dykes (e.g., the EL and ET mafic-ultramafic associations) (5). Remnants of former continental roof are represented by exotic granitoids locally associated with the EL sequences. **C.** Late Jurassic formation of atypical oceanic lithosphere (e.g. the IL and BE ophiolites) (6), consisting of the association of MORB-depleted asthenospheric residual mantle (as old as Permian), gabbroic intrusions of variable ages, and late Jurassic basaltic extrusions. Oceanic Stage. **D.** Onset of active asthenosphere upwelling, drifting and spreading (7), with formation of a more mature oceanic stage (this stage is not recorded in the known Alpine- Apennine ophiolites). Not to scale.

2) the lherzolite-pyroxenite association underwent a complete annealing recrystallization within the sp-facies stability field.

Similarly to that of the EL lherzolites, this evolution is related to the early upwelling of asthenospheric mantle accreted to the lithosphere and cooled to the regional geothermal gradient.

After the sp-facies equilibration, the ET peridotite underwent a composite decompressional evolution, recorded by:

1) the widespread partial recrystallization to plagioclase (pl)-bearing assemblages and the development of porphyroclastic to granoblastic textures;

2) the formation of tectonite to mylonite fabrics along km-scale shear zones, accompanied by progressive dynamic recrystallization to sp-, pl- and amph- bearing peridotite associations (Piccardo et al., 1990; 1992; Vissers et al., 1991; Hoogerduijn Strating et al., 1990; 1993). This late amphibole has a low-Ti pargasitic horneblende composition.

Thermobarometric estimates of equilibration conditions for the assemblages pertaining to the different textures indicate a progressive temperature decrease from sp-bearing (T ranging 1000-1100°C) to pl-bearing (T ranging 900-1000°C) to amph-bearing (T lower than 900°C) assemblages (Piccardo et al., 1992; Hoogerduijn Strating et al., 1993).

Very limited partial melting during uplift is recorded by rare pl-rich gabbroic veins, bordered by depleted peridotite walls, which cut the sp- and pl-bearing peridotite tectonites (Bezzi and Piccardo, 1971; Nicolas, 1986; Hoogerduijn Strating et al., 1990;1993). This incipient low P - low T partial melting can have occurred only in the presence of hydrous fluids or hydrated assemblages (i.e., the presence of early Ti-rich pargasite). Fluid circulation along the shear zones, as indicated by the presence of tectonites and milonites strongly enriched in later pargasitic hornblende, may even have produced localized transitions from water-deficient (and subsolidus) to water-saturated (and suprasolidus) conditions (i.e., incipient hydrous melting) (Piccardo et al., 1992).

This composite tectono-metamorphic history indicates an almost subsolidus, non-adiabatic evolution during uplift, starting from lithospheric mantle depths. This decompressional path has been related to the early pre-oceanic rifting stage in the LPB (Vissers et al., 1991; Hoogerdujin Strating et al., 1993) and is consistent with mechanisms of tectonic unroofing following passive and asymmetric extension of the lithosphere (Hoogerduijn Strating et al., 1990;1993; Vissers et al., 1991; Piccardo et al., 1992).

In conclusion, the ET peridotites may be interpreted as former sub-continental lithospheric mantle which evolved toward shallow levels along subsolidus P-T paths during the Permian-Mesozoic rifting stage. The leading mechanism for this evolution is believed to be the passive and asymmetric extension of the lithosphere (Vissers et al., 1991; Hoogerduijn Strating et al., 1993).

Final remarks on the Ligurian peridotites and ophiolites

The above sections highlight some basic features ruling the mantle history of the Ligurian ophiolitic peridotites.

1) The Ligurian ophiolites include large fragments of lithospheric mantle representing (at least for the EL lherzolites) previous asthenosphere accreted to the lithosphere during Proterozoic times.

2) The accreted fertile asthenospheric mantle underwent annealing and was thermally and mineralogically equilibrated to the regional geotherms,since it was transformed into lithospheric mantle.

3) The Ligurian ophiolites include huge bodies of former asthenospheric upper mantle which has been depleted by a Permian melting. This depleted mantle subsequently underwent a subsolidus history predating the injection of gabbroic rocks. After intrusion, the gabbros in turn record a high temperature subsolidus deformation and recrystallization from granulite/amphibolite to greenschist facies conditions.

All these features are related to the pre-oceanic rifting stage.

4) Peridotite rocks from all settings and the associated gabbros were affected from late Jurassic ocean-floor exposure by low grade overprint and metasomatic alteration (i.e., serpentinization and rodingitization), and finally they were cut by basaltic dykes and overlain by ophiolitic breccias and pillow lavas.

THE ALPINE EVOLUTION OF THE VOLTRI MASSIF PERIDOTITES.

The Erro-Tobbio meta-peridotite

The ET mantle lherzolites underwent a composite tectono-metamorphic history during alpine evolution marked mainly by several stages of recrystallization of olivine (ol) + titanian clinohumite (Ticl)-bearing assemblages (Piccardo et al., 1988; Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991). The development of such assemblages is assumed to be coeval with the widespread formation of omphacite (omp) + garnet (gar) + Mg-chloritoid (cld) + zoisite (zoi) ± talc (tlc) ± tremolite (tr) in Mg-meta-gabbros (Scambelluri et al., 1991; Messiga et al., unpublished) enclosed as former MORB-type gabbro dykes within the peridotite. Structural analysis of the ET peridotite (Scambelluri et al., 1991) indicates that development of the ol + Ticl assemblages equally occurs in low- and high-strain domains.

Alpine undeformed meta-peridotites

In low-strain meta-peridotites the original ol + opx + cpx + sp mantle assemblage is partially replaced by mesh chrysolite(chr) + tremolite(tr) + and chlorite(chl) + magnetite (mt) (Fig. 4) related to ocean-floor metamorphism at the end of rift evolution. The prograde alpine evolution is testified to by subsequent development of antigorite (atg)+ mt ± brucite (brc) veins dissecting earlier mantle and oceanic assemblages (Fig. 4). All the above microtextures are in turn overgrown by neoblastic random aggregates of ol + atg + Ticl + mt ± diopside (di) representing the peak metamorphic assemblage. Other particular structures of the peak event are veins filled by the same ol + Ticl + di + mt + chl assemblage (Piccardo et al., 1988; Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991).

During an early stage of retrogression the peak assemblage is statically overgrown by atg + oxides or atg + brc, whereas the latest retrograde stages are characterized by development of tr + chr coronas between relics of mantle clinopyroxene and fine-grained antigorite- bearing aggregates (Piccardo et al., 1988).

Alpine serpentinite mylonites

Serpentinite (antigorite) mylonite shear zones define high strain horizons within the ET peridotite; they isolate peridotite cores of variable dimensions (up to some kilometers) that still retain mantle structures and assemblages. Most serpentinite mylonite zones show a gradual transition from partially serpentinized peridotite at the margin, to strongly foliated serpentinite mylonite in the core. These changes reflect progressive syn-kinematic hydration of the peridotite within the shear zones. Development of single and/or multiple sets of shear bands, as well as folding and crenulation of the shear-induced foliations, point to a progressive thrust displacement along the mylonite zones.

Within the serpentinite mylonites the ol + Ticl + atg + mt ± di ± chl assemblage develops along single and multiple sets of shear bands deforming a preexisting antigorite, olivine-free, shear foliation. The olivine-bearing extensional crenulation cleavages (ecc) consist of fine-grained ol + Ticl + mt + atg ± di assemblages; chlorite layers commonly occur parallel to the shear bands and appear to coexist with the above assemblage. Veins filled with coarse ol + Ticl + mt + chl ± di are widespread in mylonite horizons and developed at several stages during the deformation history. Some early veins crosscut the antigorite (ol-free) prograde foliation and are dissected by the ol+Ticl-bearing shear bands. The shear bands, in turn are locally cut by a second generation of ol-bearing veins. In many cases these structures are overgrown by post-kinematic radial aggregates of coarse ol + brc.

Progressive thrusting led to crenulation of all the above structures and to flattening of the ol + brc aggregates: this stage is related to the development of atg + mt cleavages following olivine breakdown and onset of retrogression. Other retrogressive transformations include thin layers and aggregates of atg + brc grown at the expence of ol-bearing aggregates. A younger set of antigorite-bearing crenulation foliations and ecc indicate late stage extensional reactivation of part of these composite shear zones.

The high pressure overprint in metagabbroic dykes

During the alpine evolution of the ET peridotites, most dykes, previously partly or totally rodingitized, were sheared and transformed into meta-rodingites (Piccardo et al., 1980); they are characterized by fractured, rotated and partly replaced clinopyroxene porphyroclasts in a foliated di + gar + zoi + chl + mt aggregate (Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991).

The eclogite history recorded by non-rodingitized meta-gabbros is multistage through several reaction episodes resulting in different coronitic assemblages in low strain meta- gabbros (Messiga et al., 1995). The following coronas developed between igneous olivine and plagioclase: opx + chl + gar ± cld; tlc + cld + tr ± gar. These transformations are cofacial with the development of jadeite(jd) + zoi ± gar saussurite after igneous plagioclase, and of omp + gar after primary clinopyroxene. Analysis of shear-enhanced equilibrium assemblages in high strain meta-gabbros indicates that the high pressure paragenesis in olivine-plagioclase systems is made of omp + cld + gar + zoi ± tlc (Scambelluri et al., 1991; Messiga et al., 1995).

The pressure-temperature conditions for this stage are evaluated at about 20-23 Kb and 550-600°C. Glaucophane is absent in such assemblage, as it forms with chl + paragonite(par) + margarite(marg) ± tlc after cld, gar and omp during retrograde stages of metamorphism. Further retrogression is marked by the development of albite(ab) + epidote (ep) + chl + tr.

Thin ol + Ticl veins (up to 0.5 m in length) locally occur in the peridotite close to sheared gabbroic dykes. The veins are at high angle to the dykes and run from the deformed margin into the surrounding peridotite. In addition, some fractures bend into the margins of the gabbroic dykes without displacement of the gabbro-peridotite contact. These relations suggest that the high pressure ductile deformation in gabbros was coeval with brittle fracturing and vein development in peridotite wall rocks (Scambelluri et al., 1991).

Final remarks on the Alpine Erro-Tobbio meta-peridotite

Structure and petrology of the ET peridotites demonstrate that, after mantle and oceanic evolution, they underwent a complete metamorphic cycle related to Alpine subduction and collision (Hoogerduijn Strating et al., 1990; 1993; Vissers et al., 1991; Scambelluri et al., 1991). Deformation was mainly localized in serpentinite mylonite shear zones which were continuously activated under progressively changing metamorphic conditions. Within peridotite cores bounded by the shear zones, the alpine transformations are essentially strain absent, and deformation is mainly accomplished by brittle failure and veining (Scambelluri et al., 1991).

Main mineral reactions and phase transitions are summarized in Fig. 4 and point to the following sequence of events:

1) Prograde evolution from chrysotile- to antigorite-bearing assemblages: the latter are coeval with the formation of serpentinite mylonites and of antigorite shear foliations.

2) Transition from antigorite-bearing to olivine-bearing assemblages: the latter are indicative of peak metamorphic (eclogite) conditions and development of early veins, shear bands, and radial aggregates.

3) Olivine breakdown and retrograde formation of antigorite assemblages during crenulation of the previous structures.

Field relationships demonstrate that part of the ol+Ticl- bearing veins within undeformed peridotites are coeval with the deformation and high pressure recrystallization of the gabbroic dykes (Scambelluri et al., 1991). The estimate of peak eclogite conditions in Mg-Al metagabbros (20-25kb, 550-600°C) plots within the chlorite-antigorite peridotite field, defined by Jenkins (1981), and where fluorine-free titanian clinohumite is still stable (Engi and Lindsley, 1980).

Petrological data on the high pressure assemblages within the Erro- Tobbio peridotite-gabbro sequence indicate that these rocks still retain considerable amounts of hydrated phases at about 60 kilometres depth in subduction environments.

The Beigua antigorite serpentinite

The Beigua serpentinite locally displays primary stratigraphic relations with oceanic cover sequences of metasediments and metavolcanics, and preserve mineralogical and textural relics related to various metamorphic events (Cimmino et al., 1979). The earliest stage is related to a partial low- grade hydration producing lizardite(lz) and chrysotile(chr) + magnetite(mt) + chl from mantle minerals. Subsequent widespread growth of antigorite is the most evident alpine metamorphic feature (Piccardo et al., 1980). These stages are locally overgrown by partial dehydration reactions producing an equilibrium assemblage of ol + atg + di + Ticl. This prograde evolution closely resembles that of the ET meta-peridotite (Fig. 3) and is indicative of subduction driving to a peak eclogite stage of metamorphism and producing the above olivine-bearing assemblages in ultramafic rocks (Cimmino et al., 1979). The pressure constraint on this eclogite stage is given by a gar + omp + rutile(rt) assemblage in the associated mafic eclogites, which are currently interpreted as deriving from precursor MORB-type gabbros and basalts (Cortesogno et al., 1977; Piccardo, 1983; Ernst et al., 1983). Estimates on the peak eclogite assemblage in the meta-gabbros yield values of 13 kb minimum pressure and 450- 500°C (Messiga et al., 1983; Messiga and Scambelluri, 1991).

Late stage hydration and recrystallization of atg + chl in serpentinite rocks testifies to a retrograde metamorphic event (Cimmino et al., 1979; Piccardo et al., 1980). This stage corresponds in the eclogitic meta-gabbros to albite-amphibolite and to greenschist-facies recrystallization assemblages due to exhumation of the high pressure Beigua unit.

DISCUSSION

Models for continental rifting

The rifting and breakup of the continental lithosphere is a complex thermo-mechanical process that begins with rifting, involves hundreds of kilometers of extension within the continental lithosphere, and terminates with the onset of a sea-floor spreading system (e.g. Dunbar and Sawyer, 1989; with references therein).

From the geological, structural and geophysical data on modern extensional basins, the continental rifting has been discussed on the basis of the two end-member processes: the active and the passive rifts (Sengor and Burke, 1978). The development of either active or passive rift systems is primarily linked to the role of asthenosphere during inception of the rifting process. Active rifts develop when lithosphere extension is mainly driven by body forces induced by a strong thermal anomaly in the upper mantle underneath the rift (i.e., the active upwelling of the asthenosphere by convection, diapirism or mantle plumes). Passive rifts develop when lithosphere extension is mainly driven by externally applied tensional forces: the underlying asthenosphere passively wells up following thinning and stretching of the lithosphere.

The active mantle models, where mantle convection and asthenosphere diapirism are seen as responsible for doming and extensional fracturing in the lithosphere (Crough, 1983; Turcotte and Emerman, 1983; Mareschal, 1983), predict a sequence of processes such as doming, volcanism and rifting. Accordingly, the axial zone of active rifts is characterized by early and abundant magmatic (volcanic) activity, predating the rift inception. The passive mantle models imply lithospheric stretching and fracture which upset the pressure / temperature balance in the pre-rift asthenosphere and produce syn-rift depressurization; a sequence of rifting, uplift and volcanism is, accordingly, suggested. Decompressional partial melting of the asthenosphere is a consequence of its passive upwelling.

Two major theories have developed through time on the processes leading to the passive extension of the continental lithosphere: pure shear models and simple shear models.

Pure shear models (Hamilton & Myers, 1966; Stewart, 1971; McKenzie, 1978) imply that extreme continental extension results from penetrative ductile stretching of the lithosphere. Pure shear of the lithosphere does not result directly in the unroofing of deeply buried rocks but instead causes rocks from intermediate and deep crustal levels to be brought nearer to the surface by stretching of the entire lithospheric column.

Simple shear models (Wernicke, 1981,1985) imply that extreme thinning of the lithosphere might occur by normal displacement along a master detachment fault or a series of imbricated faults. The detachment fault system intersects the surface and merges downdip into a ductile shear zone which penetrates the entire lithosphere, to separate an upper plate from a lower plate. During ongoing displacement, rocks from progressively deeper lithospheric levels are exposed, hence the surface exposure of sub-continental, lithospheric mantle can be produced.

Mantle active rifts and pure shear-dominated rifts show a general symmetry of the most typical processes (i.e., rifting, magmatism, basin evolution) with respect to the future breakup axis. On the other hand, simple shear-dominated rifts show a general asymmetry in the overall rift geometries and in the distribution of upper and lower plate processes (Issler et al., 1989, and references therein).

Theoretical modelling (Ruppel et al., 1988) of the P-T-time evolution of rocks uplifted via pure and simple shear over the entire lithosphere suggests that i), in the case of pure shear, rocks follow nearly isothermal P-T paths, and ii), in the case of simple shear, rocks follow almost linear P-T paths with progressively decreasing temperature and pressure. In the latter case, they evolve as the foot-wall of low-angle normal faults, being in contact with progressively cooler hanging-wall rocks.

Most continental breaks show a common feature: they tend to follow preexisting trends of lithospheric weakness (young orogenic belts, suture zones, older mobile belts) and to branch around the stronger cratonic blocks (Wilson, 1968; Sykes, 1978). The mechanisms of breakup greatly depend on the presence of local weaknesses within the strength layered continental lithosphere, (Braun and Beaumont, 1987), such as granitic intrusions in the crust (weakness in the crust) and local increases in the crustal thickness (weakness in the lithospheric mantle) (Dunbar and Sawyer, 1989).

Pre-oceanic rifting and ocean opening in the Ligure-Piemontese basin

Contrasting geotectonic interpretations have been proposed in recent decades for the sea-floor emplacement of fertile lherzolites in the LPB and, more generally, for the origin of the Western Alps - Northern Apennine ophiolites.

Notwithstanding the general absence of distinctive features for active mantle rifting and for a mature mid-ocean ridge system in the LPB, some models interpret the mantle peridotites as part of mantle diapirs which have driven the rift mechanism in the basin (Nicolas, 1986, 1989). Other models, based on comparison with present-day mature oceanic basins with active spreading ridges and transform faults, consider the Western Alps-Northern Apennine ophiolites as oceanic lithosphere originating from transform faults and/or transform-ridge intersections (Gianelli and Principi, 1977; Abbate et al., 1980,1984; Weissert and Bernoulli, 1985), or along slow-spreading ridges (Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990).

Passive models interpret the Western Alps ophiolites as originating within a Mesozoic transcurrent rift zone (Ishiwatari, 1985), or within an embryonic ocean basin formed by passive extensional mechanisms (Decandia and Elter, 1969; Piccardo and Riccio, 1975; Piccardo, 1977). According to the latter models, passive extension led the sub-continental lithospheric mantle to be progressively unroofed and exposed at the sea-floor during the Jurassic continental breakup (Lombardo and Pognante, 1982; Piccardo, 1983; Beccaluva et al., 1984).

Recently, passive and asymmetric extensional models have been proposed, on the basis of geological and petrographic data, for the opening of the Western Tethys (Lemoine et al., 1987) and restoration of the Mesozoic sedimentary basins (De Graciansky et al., 1989; Stampfli and Marthaler, 1990). Similar models are supported by structural and petrological data on lherzolites and syn- extensional gabbros from the future Adria passive margin (ET peridotite: Hoogerduijn Strating et al., 1990; Vissers et al., 1991; Piccardo et al., 1992; Mt.Cervino-

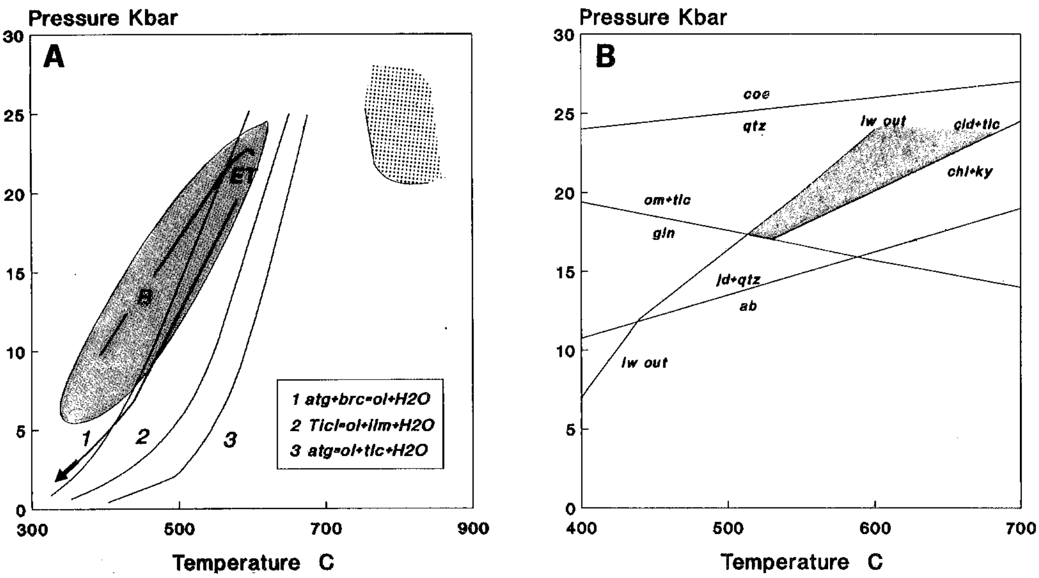

Fig. 4 — A: Pressure - Temperature diagram showing the field of high pressure equilibration of the greater part of ultramafic rocks from the Western Alps (shaded area). Garnet peridotites from the Central Alps (dotted area) are reported for comparison. Numbers 1 to 3 refer to the reaction boundaries reported in the legend. B: Beigua serpentinite; ET: Erro-Tobbio meta-peridotite. B: pressure - temperature conditions of eclogite facies metamorphism in the Erro-Tobbio meta-gabbros (shaded area, after Messiga et al., 1995).

Mt.Collon gabbro: Dal Piaz et al., 1977, 1993, Dal Piaz and Ernst, 1978; Fedoz gabbro, Trommsdorff et al., 1993; Ivrea-Verbano layered complex: Quick et al., 1992).

Mantle peridotites are fundamental lithological components of the Ligurian ophiolite associations. According to their petrological-geochemical and structural-paragenetic features, the different mantle units have different original settings in the upper mantle and significantly different mantle evolution histories. The External Liguride and Erro-Tobbio lherzolites underwent sub-solidus decompressional evolution, and were exposed at the sea-bottom during continental breakup in the LPB. They are interpreted as sections of the pre-rift lithospheric mantle which was passively involved in the pre-oceanic rift mechanisms. The Internal Liguride and Beigua depleted peridotites are interpreted as bodies from deeper asthenospheric mantle which was more actively involved in extensional processes. In fact, they most probably underwent MORB-generating partial melting during the pre-oceanic rift stage and were later exposed on the Jurassic sea-floor.

In particular, the Northern Apennine ophiolites represent, in most cases, the spatial association of Jurassic MOR basalts (+ oceanic sediments) and peridotite/gabbro rocks derived from different sub-continental settings. Sub-continental rocks (peridotites and syn- extensional gabbros) mainly formed and equilibrated in the lithosphere long before the Jurassic oceanic stage of the Ligure-Piemontese basin. They underwent a retrograde rift decompression prior to sea-floor emplacement.

Structural and petrological evidence does not relate these ophiolite sequences to active mantle mechanisms as well as to mature mid-ocean ridge - trasform fault systems. More properly, the Northern Apennine ophiolites represent the lithological associations which are expected to develop after a continental breakup due to the passive and asymmetric extension of the lithosphere, i.e., older deep rocks unroofed and exposed during the extensional processes associated with late Jurassic MORB-type basalts produced by partial melting of the upwelling asthenosphere (Fig. 3).

Passive and asymmetric extension of the Variscan lithosphere (which later evolved into the Europe and Adria passive margins) was, accordingly, the leading mechanism for the pre-Late

Jurassic continental rifting, and the late Jurassic continental breakup and ocean opening. Adria was the upper plate of the extensional system.

Partial melting of the upwelling asthenosphere began below the Adria plate and was progressively displaced towards the future LPB. The basaltic melts were first intruded into the extending Adria lithosphere (i.e., the hanging wall of the extensional system), giving rise to the pre-Jurassic syn- extensional gabbros, and were later extruded as basalt flows (i.e., the discontinuous Jurassic oceanic crust) after continental breakup. The evidence for widespread basaltic extrusions and the absence of any mid-ocean ridge system indicate that a permanent convective system was not yet active within the upwelling asthenosphere. The particular features of ophiolites from the Northern Apennines (and most probably from the Western-Central Alps) suggest that they were formed when the transition from dominant passive extension to dominant active mantle processes had not yet occurred. These latter processes should have produced the transition to a more mature oceanic stage through the inception of sea-floor spreading and the development of mid-oceanic ridges. This stage is not recorded by the known ophiolite sequences from the Alpine-Apennine system. A former wide oceanic lithosphere, poorly sampled during the Cretaceous subduction, is required by the long lived thermal low operating within the Eoalpine orogenic wedge from 130 to 65 Ma (Polino et al., 1990; Dal Piaz, 1993, personal communication).

The Ligure-Piemontese basin developed along a belt previously subjected to the Variscan orogeny. The magmatic and tectonic processes developed during the Variscan collision produced important weaknesses in the "Europe-Adria" lithosphere, which most probably acted as driving features for the future trend of the lithosphere extension.

The Permian age for the partial melting of some IL peridotites gives indications on the age of rift inception: it is, in fact, almost coeval with the post-Variscan extension recorded by the Austroalpine and Southalpine units recently interpreted (Dal Piaz, 1993) as signatures of the late Palaeozoic onset of asymmetric extension within the "Europe-Adria" lithosphere.

According to Dal Piaz (1993), the late Palaeozoic processes in the Austroalpine, Southalpine and Pennine basement of the North-Western Alps, traditionally interpreted as evidence of an ensialic mobile belt or a trench-arc system, represent the post-Variscan metamorphic and magmatic signatures of the late Palaeozoic onset of lithosphere extension within the Europe-Adria plate system. Extension was driven by simple shear mechanisms and evolved into an asymmetric continental rifting, where the future Adria acted as the upper plate. Huge pre-Jurassic gabbroic bodies, some of which as old as the Permian (e.g. Mt.Cervino-Mt.Collon: Dal Piaz et al., 1977; the Ivrea-Verbano Complex: Voshage et al., 1990; the Fedoz gabbro, Trommsdorff et al., 1993; the Koralpe and Saualpe gabbros: Thoeni and Jagoutz, 1992) were emplaced beneath and within the thinned Adria continental crust. Their occurrence supports the hypothesis that the extensional processes, accompanied by asthenosphere partial melting, were already active before the Permiam/Triassic boundary (Dal Piaz and Ernst, 1978; Dal Piaz, 1993).

Alpine subduction

The high pressure meta-peridotites and serpentinites from the Voltri Massif provide classic case studies that can be used to interpret other peridotite massifs from the Western Alps. Similarly to the Beigua and Erro-Tobbio peridotite, ultramafics from the Western Alps and Corsica are generally hydrated meta-peridotites and serpentinites: during subduction and high pressure metamorphism, both depleted and fertile peridotites develop the hydrated antigorite-bearing assemblages reported in Table 1. The ultramafic bodies from Corsica are generally associated with ophiolite slices with a blueschist to eclogite low-temperature overprint (Ohnenstetter et al., 1976; Caron and Pequignot, 1986), and develop an atg + di + mt ± Ticl assemblage where metamorphic olivine is most probably absent (Ohnenstetter et al., 1976). On the other hand, the high pressure assemblages of peridotite massifs from the Western Alps are olivine-bearing, and descriptions of ol+Ticl-bearing assemblages are available in the current literature for the Monviso (Lombardo et al., 1978) and Lanzo Massifs (Sandrone et al., 1986; Biino et al., 1988) and the Zermatt Saas zone (Bearth, 1967; Dal Piaz et al., 1980; Fleckenstein and Voll, 1982). Similarly to the Beigua and Erro-Tobbio units of the Voltri Massif, these ultramafics

Table — High pressure mineral assemblages in Alpine metaperidotites.

Corsica[1]	atg + mt + di + hygr + chl ± Ticl
Western Alps	
Voltri Massif *(Beigua*[2] *and Erro-Tobbio*[3] *Units)*, Lanzo[4]**, Monviso**[5] **and Zermatt**[6]	ol + Ticl + atg + di + chl + mt
Central Alps	
Cima di Gagnone[7]**, Alpe Arami**[7, 8]**, Duria**[7]	gar + ol + opx + cpx ± amp ± Ticl

[1]Ohnenstetter et al., 1976; [2]Cimmino et al., 1979; [3]Scambelluri et al., 1991; [4]Sandrone et al., 1986; [5]Lombardo et al., 1978; [6]Bearth, 1967; [7]Evans and Trommsdorff, 1978; 1983; [8]Mockel, 1969.

underwent pervasive recrystallization, developing ol + Ticl + atg peak assemblages. Some constraints indicative of the pressure - temperature conditions of recrystallization are given by the associated eclogitic meta-gabbros. In the Monviso massif, gar + omp + rt assemblages in Fe-Ti meta-gabbros (Lardeaux et al., 1987), as well as gar + omp + cld + zoi assemblages in meta-troctolites and Mg-Al meta-gabbros (Kienast and Messiga, 1987), point to pressure-temperature estimates of 15 kb and 500°C. Within the Lanzo meta-peridotite, gar + omp (Pognante and Kienast, 1987) and gar + omp + cld + tlc (Kienast and Pognante 1988) assemblages in meta-gabbros developed at 15-18 kb and 400-500°C have recently been described. Peak eclogite determinations for the Zermatt Saas zone are widespread in the literature (Chinner and Dixon, 1973; Ernst and Dal Piaz, 1978; Meyer, 1983; Ganguin, 1988; Barnicoat and Fry, 1987) and point to the development of kyanite(ky)-gar-omp-bearing assemblages at 20 kb minimum pressure and 600°C (Barnicoat and Fry, 1987). The presence of ultra-high pressure (26-28 kb and 590-630°C) in the Cignana meta-ophiolites (Northern Aosta Valley) has been recently documented from the association of coesite + Mn-Mg garnets (Reinecke, 1991).

Hydrated ultramafics from the Western Alps thus re-equilibrated at high pressure within the ol + atg + Ticl field of Fig. 4. Compositional data are available mainly for the Voltri Massif meta-peridotites and indicate that Titanian clinohumite is mostly fluorine-free: as a consequence the maximum temperatures should not exceed the Ticl-out curve of Fig. 4. In any case, the presence of antigorite in all high pressure assemblages definitely constrains the temperature values below the atg-out boundary. A large part of the ultramafics from the Western Alps thus recrystallize to ol + atg + Ticl + di under eclogite facies conditions in the range of 450-600°C and pressures up to 25 kb.

The prograde history shown in Fig. 4 for the Erro-Tobbio peridotite is synchronous with the development of continuous deformation in a compressive regime during subduction. At peak pressure conditions, a reversal in the shear senses is observed in all high pressure rocks: this fact is interpreted as a change from compression to extension, occurring at deep levels of subduction zones and driving the exhumation of the high pressure nappes (Scambelluri et al., 1993).

More extreme conditions characterize the high pressure recrystallization of garnet peridotite at Cima di Gagnone, Alpe Arami and Duria in the Central Alps (Mockel, 1969; Evans and Trommsdorff, 1978, 1983; Ernst, 1977). These rocks develop a gar + ol + cpx + opx ± amph assemblage (Table), indicating pressure - temperature conditions of 20-25 kb and 800°C (Evans and Trommsdorff, 1978). In particular, garnet peridotites from Cima di Gagnone preserve relics of titanian clinohumite that escaped the prograde transformations to ol + Mg-ilmenite(ilm) according to the breakdown reaction of Fig. 4. Depending on its fluorine content however, clinohumite may pertain to the garnet-bearing assemblage, as small amounts of fluorine stabilize the titanian clinohumite to much higher temperatures (Evans and Trommsdorff, 1983). Therefore, an atg+Ticl-bearing assemblage predates the equilibration in the garnet lherzolite field and suggest that a partially serpentinized peridotite is the precursor rock of the Cima di Gagnone garnet peridotite (Evans and Trommsdorff, 1978). This is confirmed by the occurrence of metarodingite dykes within the garnet peridotite, indicating the high pressure recrystallization of assemblages deriving from the low grade metasomatism of originally mafic dykes (Evans and Trommsdorff, 1978; Evans et al., 1979).

Ultramafic rocks from the Western Alps are thus hydrated meta-peridotites which constitute large volumes within ophiolite nappes and must be considered a relevant part of the subducted oceanic lithosphere. Recent models on fluid and rock behaviour in subduction zones (Peacock, 1993, with reference therein) adopt average basaltic compositions as representative of the subducted oceanic crust, and hypothesize a significant fluid release in high pressure environments due to dehydration of wet basaltic rocks. Our studies on the alpine peridotites highlight that i), peridotite rocks are a significant part of the oceanic lithosphere and wet ultramafics should be more thoroughly considered in these models; ii), peridotite rocks in high pressure environments develop stable hydrated phases in large modal proportions up to 600°C and 25 kb, thus demonstrating that, apart from partial dehydration of antigorite to olivine, water is strongly retained in peridotite systems; and iii), the associated eclogitic meta-gabbros (i.e., mafic rocks) develop hydrated high pressure assemblages with chloritoid, talc and zoisite as main phases. Recent experimental data on mafic rocks (Poli, 1993; Poli and Scambelluri, 1993) and direct studies on natural meta-gabbros (Messiga et al., 1995) demonstrate that hydrous assemblages are stable at high pressure. As a consequence, large amounts of water are retained in the subducted slab. This fact has relevant consequences on rock rheology and on metasomatism of the overlaying mantle wedge due to fluid release in the slab.

Considering the dry assemblages particular to meta-peridotites from the Central Alps, and the possibility of serpentinite precursors for part of these rocks, transition from Western Alpine to Central Alpine meta-peridotite types represents an important source of metamorphic fluids at depth.

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